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Analysis of Leak and Explosion from an Underground Pipeline in Kaohsiung, Taiwan

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Abstract

On 23:57 July 31st, 2014, a catastrophic vapor explosion occurred in the downtown of Kaohsiung city. The incident was initiated from a leak of an underground pipeline transporting pressurized propylene liquid. Analysis of pipeline operation logs and pipeline break release modeling suggested that at least 90,000 kg of propylene leaked, entered the underground trench and spread 4.5 km in distance before meeting an ignition source three hours later. The ignition caused a significant confined vapor explosion which blew out the road above the underground trench, damaged more than one hundred vehicles on the road with thirty two fatalities and more than three hundred injuries.

This incident bears similarity to two previous incidents: the explosion in Guadalajara, Mexico, in 1992, owing to a gasoline leaked into sewer through a corroded pipeline which resulted in 252 fatalities and more than 1500 injuries (Andersson and Morales, 1992); and the explosion in Qingdao, China, in 2013, owing to a leak of crude oil from a corroded pipeline into the city storm drains which resulted in 62 fatalities and 136 injuries (Zhu et al., 2015), and. Key factors contributing to the large number of fatalities and injuries in these incidents are due to the very large quantity of flammable mass leaked, the confinement in the sewer or drain, and they occurred near or inside the well-populated communities. There was however a subtle difference in the present case in that the leak source was a pressurized, flashing liquid which would vaporize completely upon leak into ambient environment while the other two cases dealt with flammable liquids with only partial vaporization. Challenges and recommendations in addition to detailed analysis of the incident are given to prevent and mitigate the occurrence of similar incidents.

Keywords: pipeline, leak, propylene, vapor explosion

Background of the Pipeline

The incident was related to a pipeline connecting the LCY Chemical Corporation Tashe Plant and the harbor terminal company, China General Terminal & Distribution Corporation (CGTDC). It was a four inches pipe buried about 1 m below grade with a total distance of about 27 km solely devoted to transporting pressurized, liquid propylene. Its route was planned in 1986 and operation started in 1993. A total of three underground pipelines, one 8-in ethylene line, one 6-in propylene line, and one 4-in propylene line, were built at the same time by Taiwan CPC Corporation and the 4-in line was transferred to LCY after the erection. Initially, the 4-in line was connected to the Taiwan CPC Corporation Cianjhen terminal. Subsequently, an extension line to CGTDC terminal was built as a second supply source. Although planning of the pipeline route had carefully avoided the major downtown residential area, most part of the pipeline was now surrounded by commercial and residential buildings.

Event leading to the explosion

The incident was first reported from an unknown fog to come out intermittently from roadside rainwater trench covers and manholes of the storm trench beneath the junction of Ersheng 1st Road and Kaixuan 3rd Roads in downtown Kaohsiung City on 20:46 July 31st 2014, as shown in the inserted photos (a), (b) and (d) in Figure 1. Fire fighters from Kaohsiung City Fire Bureau reached the site on 20:50, secured the area and began spraying water on the fog. An incident command post was also setup in the foot path of the road junction. Efforts were made to identify the leak materials and leak source but were unsuccessful. While the fog erupting from manholes of the storm trench beneath the junction of Ersheng 1st Road and Kaixuan 3rd Roads diminished gradually, a small explosion in the manhole of storm water trench occurred about 1 km away from the initial leak scene on 22:20. The explosion however did not escalate. Around 22:50, a major white smoke was found coming out from a nearby light rail construction site underground trench opening as shown in the inserted photo (c) in Figure 1. This opening was then considered as the source of the leak and the site was considered as the hot zone with restricted entry. Air samples were also taken back for analysis. Unfortunately, explosion occurred before the air sample was analyzed. Another peculiar and unresolved finding at 23:45, right before the explosion, was an intermittent suction or flowing sound from a manhole near the railroad as shown in the inserted photo (e) in Figure 1. There was however no vapor eruption from this manhole. Thus, there was no clear conclusion regarding the leak gas, the leak source and the source owner before the explosion. Formal confirmation of the leak gas to be propylene was delayed to 6:30 am the following day by residual gas on the intact storm water trench in Ersheng 1st Road. Figure 1 shows the schematic diagram of the pipeline, underground trench, the spread of the leak vapor and corresponding photos for the vapor eruption at different locations.

Investigation after the explosion revealed the pressure transmitter on the side of Taiwan CPC pipeline connected to LCY pipeline recorded a sudden drop of pipeline pressure from 4.2 MPa to 1.37 MPa on 20:43. Both CGTDC and LCY Tashe Plant did not installed pressure transmitter on their side of pipeline. Only pressure gauges and flow meters were installed. Subsequently,

LCY Tashe Plant operator found in the control room that the pipeline flow meter indicated zero flowrate. LCY operator phoned CGTDC operator in CGTDC control room. CGTDC operator found that the flowrate from the pump was abnormal and reached 33,000 kg/hr, well above the normal flow rate of 23,000 kg/hr. The operator also found that the pumping pressure was dropped from 4.0~4.5 MPa to 2.7 MPa and further dropped to 1.8 MPa, while the electric current for the pump motor rose from 120~130 amperes to 180 amperes. The operator then shut off the pump and pipeline isolation valve. The pipeline pressure dropped to 1.3~1.35 MPa after the shutoff. The engineers of the two sites discussed and decided instead of carrying out a pressure test at pumping pressure, a static pressure test with isolation valves at both sides of pipeline closed was carried out. The pipeline pressure maintained at the propylene vapour pressure of 1.3~1.35 MPa. By 22:00, LCY manager demanded to start pumping again. By 22:15 pumping restarted but CGTDC pipeline flow meter indicated a flowrate of 24,500 kg/hr yet LCY operator found that their flow meter indicated a flowrate of 6,000 to 7,000 kg/hr. Engineers of both companies agreed that such flowrate discrepancy should be resolved later. On 23:23, a CGTDC foreman for the next shift smelled propylene near Kaixuan 3rd road on his way to work. He suspected that it could be a leak from their pipeline and thus he rushed to CGTDC plant. He arrived 10 minutes later, expressed his concern to control room operators and ordered the shutdown of the pump. By 23:57, explosion occurred. Neither companies informed the Kaohsiung City Fire Bureau or any government agencies regarding the flow rate and pumping pressure abnormalities even after the explosion. The slow response and negligence of operators in combined with production oriented plant manager were the major contributing factors for the catastrophic explosion.

The Explosion and the damage

Without any warning, an explosion occurred near the command post on 23:57 July 31st. The explosion was occurring beneath the road surface with a smoke erupting out from the storm water trench manhole, followed by road surface crack, and a large fire erupted out. Figure 2 shows a sequence of frame from a recorder on a fire truck. The arrow in the first frame indicates the first smoke eruption from the manhole. The road surface was blown out and pushed upwards all vehicles and personnel on the road and then collapsed to the trench. The fire truck in Figure 2 was eventually turned upside down.

Figure 3 shows the pipeline route, the explosion affected area, the distribution of causalities, and corresponding photos for damages. The explosion propagated along the Kaixuan 3rd road to the north and south along the storm water trench. At the north end of Kaixuan 3rd road, the explosion propagated towards Sanduo 1st road and its junction to Wuqing 2nd road. A total of 4.5 km road were blown out.

The junction of Sanduo 1st road and Wuqing 2nd road suffered the largest fatalities and injuries as indicated in Figure 3. Wuqing 2nd road is famous for many midnight snack shops. A surveillance video showed that there was a red light stopping several cars and scooters right before the explosion. Another factor contributed to the significant fatalities in this area is that the road surface covering the storm water trench was only about 0.5 m which is very thin comparing with the 1 ~ 2 m in other roads. The explosion not only blew out the road surface but also shattered the road into small fragment and debris. Some of the debris was even blown up to the roof of four-floor houses as seen in Figure 3. Causalities were mostly caused by the debris impact and the explosion flame. The explosion on the Sanduo 1st road eventually diminished about 400 m east from the junction of Wuqing 2nd road.

The second largest fatalities were occurred in the junction of Kaixuan 3rd road, Ersheng road and Ersheng 1st Road which centered on the incident command post. Fire trucks that parked on the Kaixuan 3rd road were overturned by blown out road as shown in Figure 3. More than twenty fire trucks were damaged. Most fire fighters stayed near the fire trucks were injured or buried by the debris or the overturn fire trucks. Seven of the ten fatalities on this road junction were fire fighters.

The explosion damage on the south side of Kaixuan 3rd road and Yixin 1st Road was less severe compared with other area as shown in Figure 3. It is likely that most explosion energy was dissipated by the thick road surface on top of the storm water trench. Vehicles remained intact even after the blown out. There was also far less debris compared with Sanduo 1st road. An additional factor that contributed to the reduced damage was road block. Most part of Kaixuan 3rd roads were blocked after the leak and thus the explosion exposure was reduced. The explosion on the Yixin 1st road continued through the storm water trench near Guanghua 3rd road eventually vented through the No. 5 boat canal and blown out the canal terminal. The road surface on Guanghua 3rd road was however intact.

The pipeline break

Despite the complicated leaks and silence of the pipeline operators, the identification of the leak source after the explosion was straightforward without ambiguity. After the explosion, a large jet fire developed near the junction of Ersheng 1st Road and Kaixuan 3nd Road as shown in Figure 4(a). This was the largest fire after the explosion and it lasted till 6 am the following day. As the fire diminished gradually, it can be seen clearly that the fire was coming out from a branch of storm water trench as indicated in Figure 4 (b) and (c). Clearly, this would be the source of leak.
Subsequent inspection of the trench branch with jet fire revealed that there were three pipelines passing through the trench. The 4-in line was completely exposed in air and had a break opening of 4 cm by 7 cm as shown in Figure 5. The 6-in and 8-in lines were located next to the 4-in line, partially exposed in air, and remained intact. These two pipelines did not suffer the jet flame impingement from the 4-in line as they were located on the back side of the 4-in line opening. Inspection of the leaked pipeline also showed pipeline wall thickness greatly reduced from its original 6 mm to less than 1 mm by corrosion from the humid ambient environment in the trench. Thus, it is concluded that it was the LCY 4-in propylene pipeline leaked and caused the explosion.

Amount of the leak

It is important to estimate the leak rate and amount of leaked in order to assess the potential damage and evacuation zone. The leak rate was dominated by leak opening and the pipeline pressure. Figure 5(a) shows the pipeline pressure recorded at Taiwan CPC Cianjhen terminal which is a branch line to the CGTDC and LCY pipeline. As the Taiwan CPC Cianjhen terminal was close to CGTDC pumping station, the recorded pressure can be a good approximation of the upstream pressure of the leak. As the boiling point of propylene is far below the ambient pressure, the leak from the pipeline may or may not flash depending on the upstream pressure. If the upstream pressure is higher than the saturation vapor pressure, the propylene may leak out as a liquid before flashing. If however the upstream pressure is close to the saturation pressure, flashing is expected and the typical two-phase flashing flow across an orifice may be used (Crowl and Louvar, 2012).
As Figure 6(a) indicates that the pipeline upstream pressure after the break was very close to propylene saturation pressure, flashing two-phase flow will be the dominant mode of leak. Although more detailed modeling can be done for the two-phase pipe flow, Chen et al. (1995) showed that the liquid dried out is expected to occur in about 10 s for a 100 m pipeline containing liquid propane and butane. In the present case with very long pipeline and long leak time of more than 1 hr, liquid dry out was also expected near the break and the vapor choked flow equation (Crowl and Louvar, 2012) can be a good estimation of leak rate.
Figure 6(b) showed the recorded flowrate on CGTDC and LCY side. The area difference between the two records will be the amount lost during pumping and mostly in liquid form. Direct integration gives 34,000 kg. For the valve closed period, a total of 97 min, the loss is calculated to

be 56,800 kg from the vapor choked flow equation and 160,000 kg from the flashing flow equation. The latter is far larger than the possible pipeline inventory of 100,000 kg based on the 27 km of pipeline volume and propylene density. As expected, the value from vapor choked flow calculation is considered a more realistic value compared with that from flashing flow equation. Thus, a total of 90,800 kg propylene was estimated to leak before the ignition. The estimated amount of leak is far too large to be safely dispersed in air without ignition and explosion. There is also no way to safely dispose or mitigate the flammable cloud from the trench.

Spread of the leak

It is important to know how the leak in the trench was spread such that responders may take proper action in future incidents. Investigation revealed that there were two storm water trench branches as shown in Figure 7, one being directly beneath the Ersheng Road but is only 7 m in length and sealed in the other end, the other being about 10 m north of the dead ended branch and housed the pipelines. The later was then connected to the trench beneath Ersheng Road. We put up a schematic diagram in Figure 1 showing all the trenches and trench openings. The trench branch that housed the pipeline had a manhole upstream which was the manhole with the suction sound. As the pipe break was facing towards the main trench, the leak from the break would form a jet and entrained significant air from the upstream trench. The direction of the leak is thus in consistent with the finding of suction sound in the upstream manhole. It is also consistent with the fact that there was virtually no damage in Ersheng road. The vapor jet impinged on the trench beneath Kaixuan Road and spread in both direction regardless of the trench sloping as shown in Figure 1. The vapor flow was completely different from a liquid leak which would flow by gravity. The spread of the leak vapor in the underground trench was governed by the flow resistance which is in turn affected by trench size, branched flow and trench opening to ground. Branch flow is in general much smaller than line flow in a tee junction. Flow into a larger branch is also favored over a small branch. Finally, the area with most vapor escaped do not necessarily corresponds to the leak source but rather depends on the size of opening to ground. These findings will be useful for all incident commanders dealing with underground pipeline leak incidents provided that all underground trenches are well documented and available during the incident.

The probable ignition source

Another important factor contributing to the vapor explosion is the ignition source. It is crucial to identify the exact ignition source so that a better site control in any future incident can be taken. As the ignition occurred more than three hours after the leak, it is difficult to determine the exact ignition source owing to very wide range of release dispersion. A fault tree analysis was performed and a total of six possible ignition sources were identified: autoignition, driving vehicles, smoking, fire truck engine, static discharge, and open flame. Videos from road surveillance cameras, vehicle driving recorders, and reporter video cameras were collected and used to identify the direction of fire and explosion propagation as well as possible ignition sources. All videos pointed to the junction of Ersheng and Kaixuan Roads as the explosion initiation location. All possible ignition sources were excluded except for the fire trucks that parked inside the road block zone.

As the area were blocked for traffic, the only available ignition sources were the fire trucks which remained running to provide firewater. In fact, there was a fire truck near the junction of Ersheng 1st road and Kaixuan Road as shown in Figure 4(b). The engine of the fire truck after the explosion was completed burnt down, yet Figure 4(c) showed that the road sign in front of the engine remained intact. Thus the fire on the fire truck engine was unlikely to be caused by the jet fire from the leak pipeline. Figure 4(c) also showed the char from burnt fire truck tire after the removal of fire truck. The white arrow in Figure 4(c) was the location of a telephone cable junction box cover. The telephone cable junction box is not sealed but usually drained to nearby storm water trench. It is very likely that the vapor in the storm water trench spread out into the junction box, and eventually escaped the cover to meet the truck engine and ignited. The ignition resulted in flame propagation and explosion along the storm water trench with smoke eruption from the trench manhole. With flame accelerated along the trench, the explosion intensity also increased. Eventually the road surface blew out with erupted flame. The explosion propagated through the entire trench that filled with flammable vapor.

The analysis suggests the importance of strict control of ignition source during a flammable release. In fact, the only safe outcome of such a large release of flammable vapor into a confined space is a slow dilution to below flammability limit. Either premature ignition or recovery of flammable vapor is extremely difficult and risky to do.

Recommendations and Conclusions

A large leak of flammable liquid or vapor from a pipeline into an underground confined space such as a storm water trench is a recipe of disaster. It is difficult to identify and stop the leak source. It is also extremely difficult to recover or dispose the leak from the confined space. Control of ignition source is also difficult owing to numerous opening to ground. In fact, the only safe outcome of such a flammable leak is continuing dilution to below flammable limit. It is recommended that all risk assessment of underground pipeline should include analysis on the potential leak into nearby trench. This will be the largest risk associated with an underground pipeline.

To safely dilute the flammable leak, we propose a concept of suppression the flame propagation rather than the explosion overpressure by injecting inert gas into the underground duct. Experimental studies (Lin et al., 2017) were carried for the suppression by an inert gas of flame propagation in one section of a tube to another section filled with flammable mixtures. The critical length of the inert gas section required for successful suppression is determined to be less than 0.3 m for a 3-m ignition section containing propylene/air mixture near stoichiometric concentration. To suppress the flame propagation, one simply need to inject inert gas into the duct at fixed intervals. The best point of injection of inert gas will be the manhole to the underground trench. Tests are planned by using a large duct with an internal diameter of 0.5 m to provide a near-field-scale validation for the current results. It is hoped that the above *inertia isolation* method can provide a way to prevent the catastrophic explosion upon a large flammable leak into underground trench

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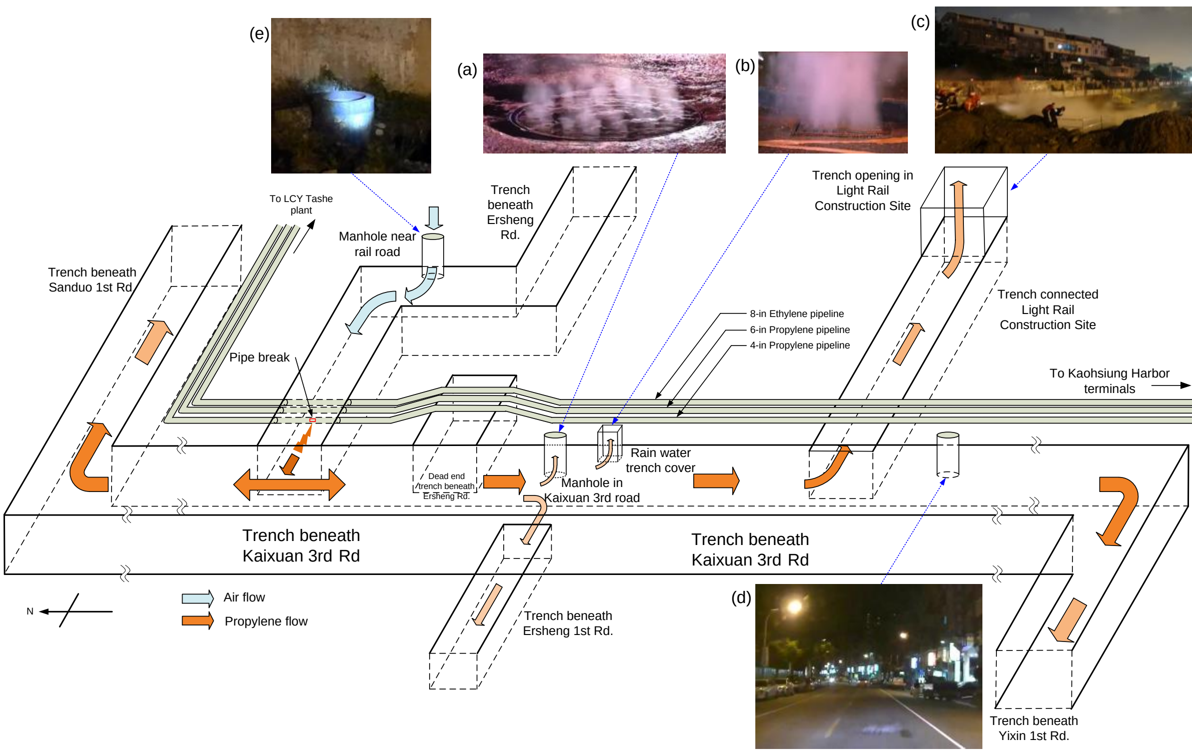

Figure 1: Schematic diagram of the pipeline, underground trench, the spread of the leak vapor and corresponding photos for the vapor eruption at different locations.

Figure 2: Sequence of explosion recorded on a fire truck in Kaixuan 3rd road facing south bound.

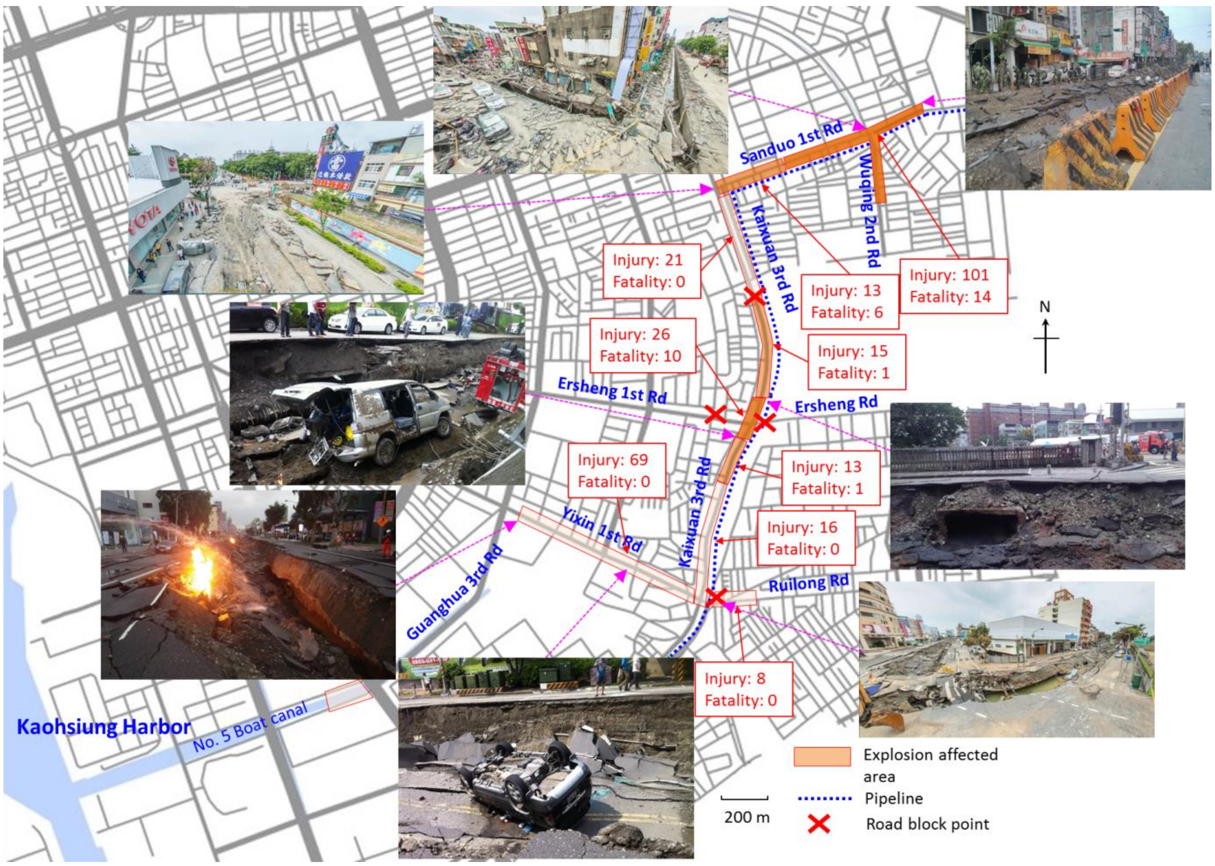

Figure 3: The pipeline route, the explosion affected area, the distribution of causalities, and the corresponding photos for damages.

Figure 4: Photos of the fire after the explosion on the north side of junction of Kaixuan 3rd road and Ersheng 1st road. Time of the photos: (a) 12:00 am (b) 06:00 am (c) 07:05 am. Red arrow indicates the location of storm water trench branch with the leaked pipeline. Yellow arrow indicates the fire truck engine suspected to be the ignition source. White arrow indicates the char from burnt fire truck tire. Note for the road sign in front of the engine remained intact.

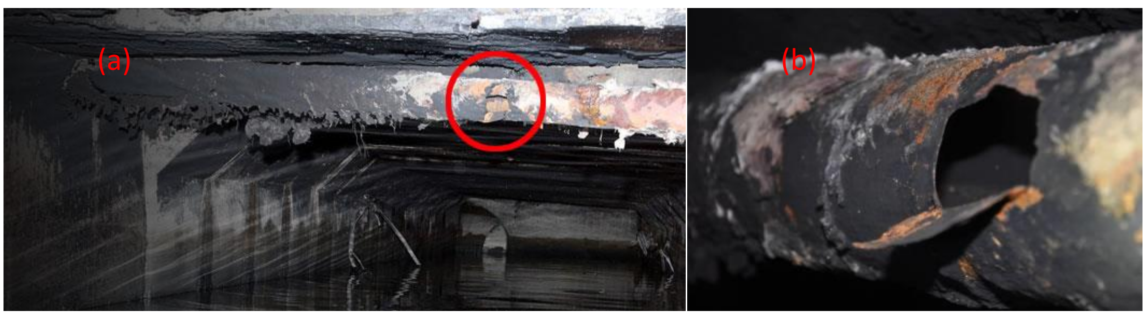

Figure 5: Photos of (a) the storm water trench, the 4-in propylene pipeline and the break, (b) close view of the break opening.

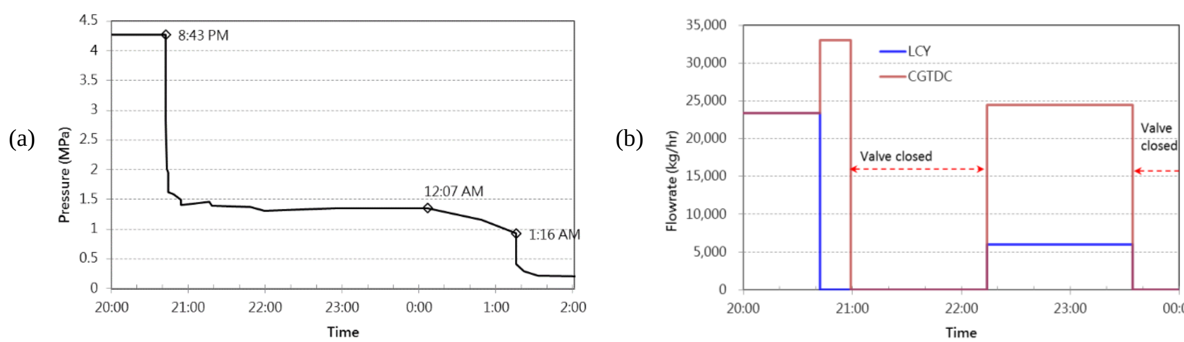

Figure 6: (a) Pipeline pressure recorded at Taiwan CPC Cianjhen terminal, a branch line to the CGTDC and LCY pipeline. (b) Recorded flowrate on CGTDC and LCY side

Figure 7: Photo of the storm water trench branches, the left one housed the pipelines and the right one was sealed in the other end with a total length about 7 m.